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Final Report

Cavendish Balance Automation

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National Aeronautics and Space Flight Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

ATTN: Tony Robertson

Submitted by:

TMET
P.O Box 83
Winchester, TN 37398
Phone 256-527-2034
Email bryanmel@yahoo.com
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Cavendish Balance Modification

This report is the final task for the Purchase Order Number H32721D titled “Cavendish Balance Modification”.

The scope of this project was to modify an off-the-shelf manually operated Cavendish Balance to allow for automated operation for periods of hours or days in a cryostat. The purpose of this modification was to allow the balance to be used in the study of effects of superconducting materials on the local gravitational field strength to determine if the strength of gravitational fields can be reduced. A Cavendish Balance was chosen because it is a fairly simple piece of equipment for measuring gravity, one of the least accurately known and least understood physical constants.

The principle activities that occurred under this purchase order were:

- 1: All the components necessary to hold and automate the Cavendish Balance in a cryostat were designed. Engineering drawings were made of custom parts to be fabricated, other off-the-shelf parts were procured.
- 2: Software was written in LabView to control the automation process via a stepper motor controller and stepper motor, and to collect data from the balance during testing.
- 3: Software was written to take the data collected from the Cavendish Balance and reduce it to give a value for the gravitational constant.
- 4: The components of the system were assembled and fitted to a cryostat. Also the LabView hardware including the control computer, stepper motor driver, data collection boards, and necessary cabling were assembled.
- 5: The system was operated for a number of periods, data collected, and reduced to give an average value for the gravitational constant.

Cavendish Balance

The Cavendish Balance used in this experiment was TEL-Atomic model TEL-RP2010. Figure 1 shows an unmodified balance. Not shown in the figure but supplied with the balance is a control box that interfaces with the balance and converts the capacitive measurements into a proportional voltage signal that can be collected by standard data acquisition systems.

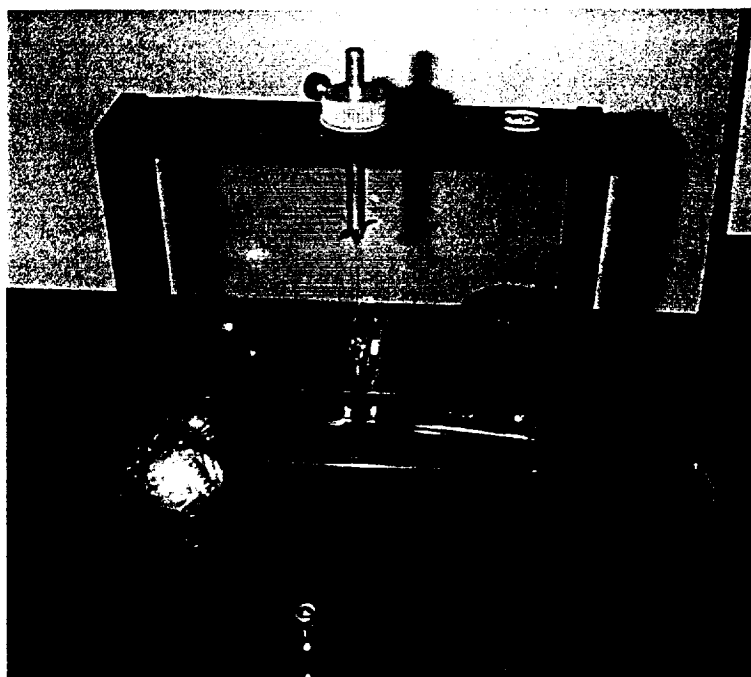


Figure 1. Cavendish Balance

The balance is basically a bench top model designed for manual operation. The large lead masses are moved back and forth by hand and the effect on smaller masses hung on a torsional pendulum are noted. At first the large masses are moved back and forth to get the small masses rotating. The small masses rotate to some position due to gravitational attraction between small and large masses then start to rotate in the other direction due to the torsion in the pendulum beam. The large masses are quickly rotated to the opposite side at the end point of the torsional pendulum swing to built up the swing amplitude. After this is done for a number of times the large masses are moved to a center position and the pendulum is allowed to damp down for a number of periods. From the angular displacements of the smaller masses the gravitational constant can be calculated. The angular displacements of the smaller masses can be measured

thru the use of a laser aimed at a mirror on the pendulum, however the TEL-Atomic balance has a capacitive type angular displacement transducer which has the advantage of reducing the error due to non-rotational movements.

Component Design

The first step in the modification process was to design all of the components necessary to hold the balance and automation components in a cryostat. The system had to be fairly compact for several reasons. The available cryostat was not very large and was built in such a way that a large amount of the space inside could not be used. Another limitation was imposed due to the short length of cable between the balance and the interface box that goes with it. The cable could not be easily lengthened without changing the capacitance of the cable and thereby affecting the measurement being made. Also the interface box could not be exposed to the extreme temperatures without affecting the calibration.

A stepper motor drive was chosen as the best method to automate the movement of the large masses. A worm gear drive arrangement was used to provide a large gear reduction ratio and prevent excess movement by the masses because of the self-locking nature of worm drives. Because of the very cold temperatures involved Rulon bearings were chosen. The major structural components in the system were made of G-10, a nonmetallic material. The purpose of this was to avoid any interferences due to metallic compounds. Also the system designed was symmetrical so that unbalanced gravitational forces would not be imposed on the experimental apparatus.

Figure 2 shows the structure designed to hold the balance in the cryostat. The balance is mounted to the bottom plate which is suspended from the top plate with four rods. The top plate serves as a cover plate for the cryostat as well as a support member. The large masses are suspended from and rotate on a central rod with a cross member to correctly locate them on either side of the balance. A gear is located at the top of the shaft which meshes with the worm gear on the stepper motor shaft. Provisions are made for the wiring leading from the balance, thermocouple fittings,

and fill tubes to add liquid nitrogen to the cryostat. Also about 5 inches of insulation were added to the underside of the top plate to avoid heat transfer into the cryostat.

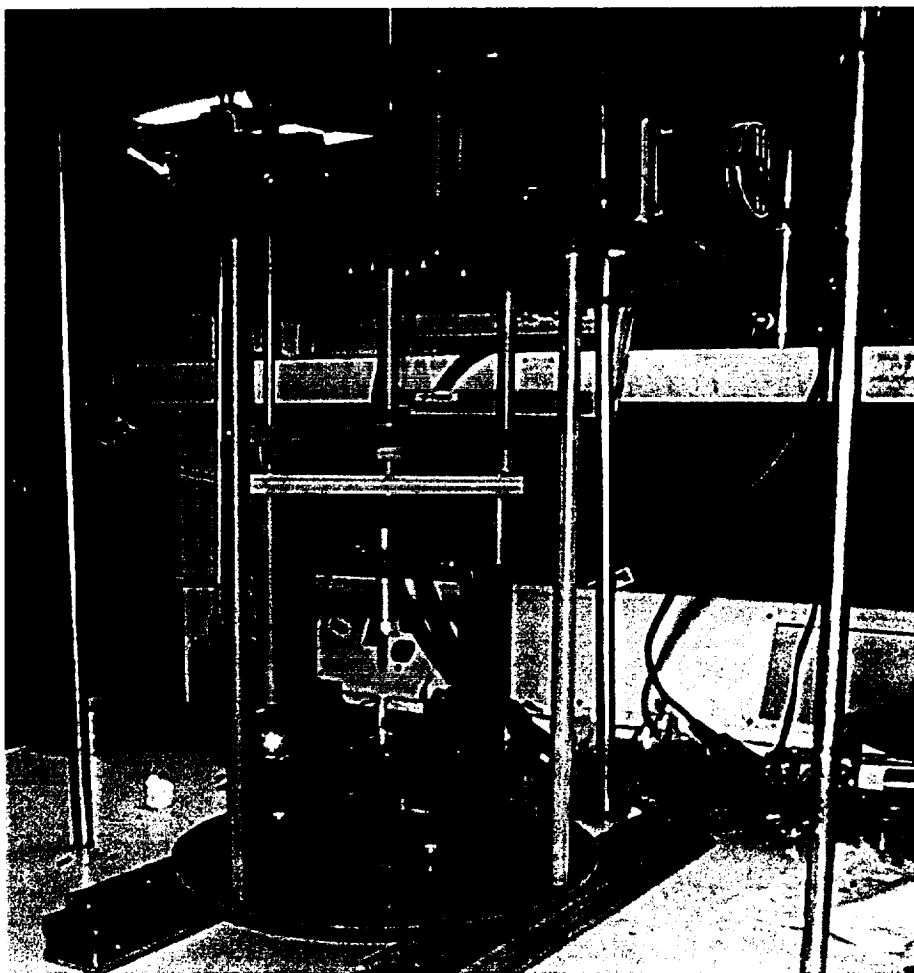


Figure 2. Modified Balance Components

Automation Software

LabView software was chosen to control the automation process and to collect data from the balance due to its flexibility, the large number of hardware accessories controllable by the software, and the ease of use. Currently the program is run on a National Instruments PXI based rack mount computer. A picture of part of the interface for the software is shown in Figure 3.

A significant amount of time was spent writing the software due to the complicated nature of the operation of the balance and the necessity of moving the large masses at the correct end points of the pendulum travel so as to get an unbiased gravitational constant value. The software as written collects a large number of data points per second and averages those points. The reason a large number of points are collected and averaged is because of the poor quality of data taken from the balance. The average values are then used in determining the slope of a line which represents the position of the torsional pendulum. When the slope of the line approaches zero the pendulum is approaching an end point. Other control code has been added to start the device from a quiescent state, to handle data that can be noisy at times, and to handle other perturbations. Another part of the software handles the positioning of the large masses by the stepper motor driver and stepper motor. The positioning of the end points, middle point, rotational speed, and acceleration rate are all controllable in the software. A third area of the software controls the saving of data to a text type data file.

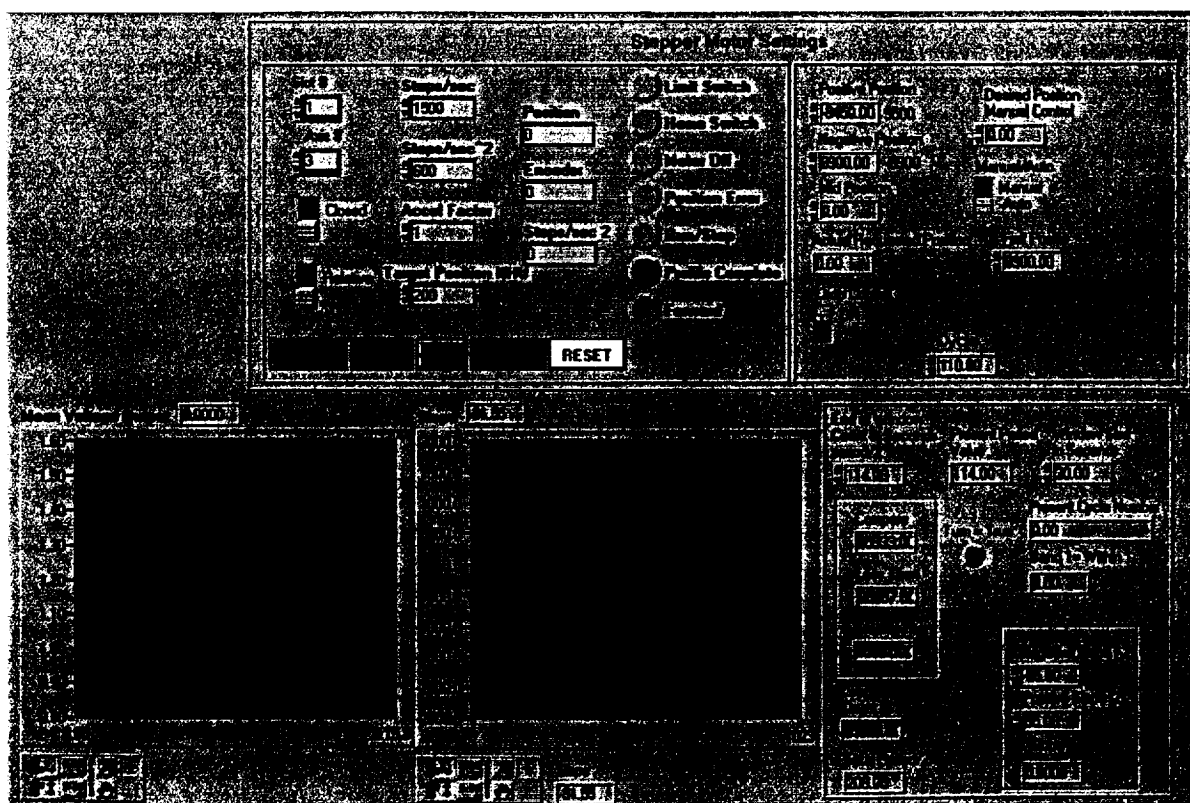


Figure 3. Automation Software

Data Reduction Software

Software was also written to reduce the data taken from the balance. The data collection program saves data at a rate of one data point per second. This is a fairly slow data rate, however since a typical test run might last 12 to 24 hours a significant amount of data is generated. The primary points of interest in the data are the turning points or peaks so a LabView program was written that uses a curve-fitting route to determine the peak points, thereby reducing the data volume greatly. A second program was written to handle the actual calculations necessary to determine the gravitational constant. These calculations could be done on a calculator but are very lengthy and would have to be done over and over. Basically the turning points are imported into the program and a few other variables representing physical properties of the setup are entered. The program then calculates the gravitational constant for each cycle made during the run.

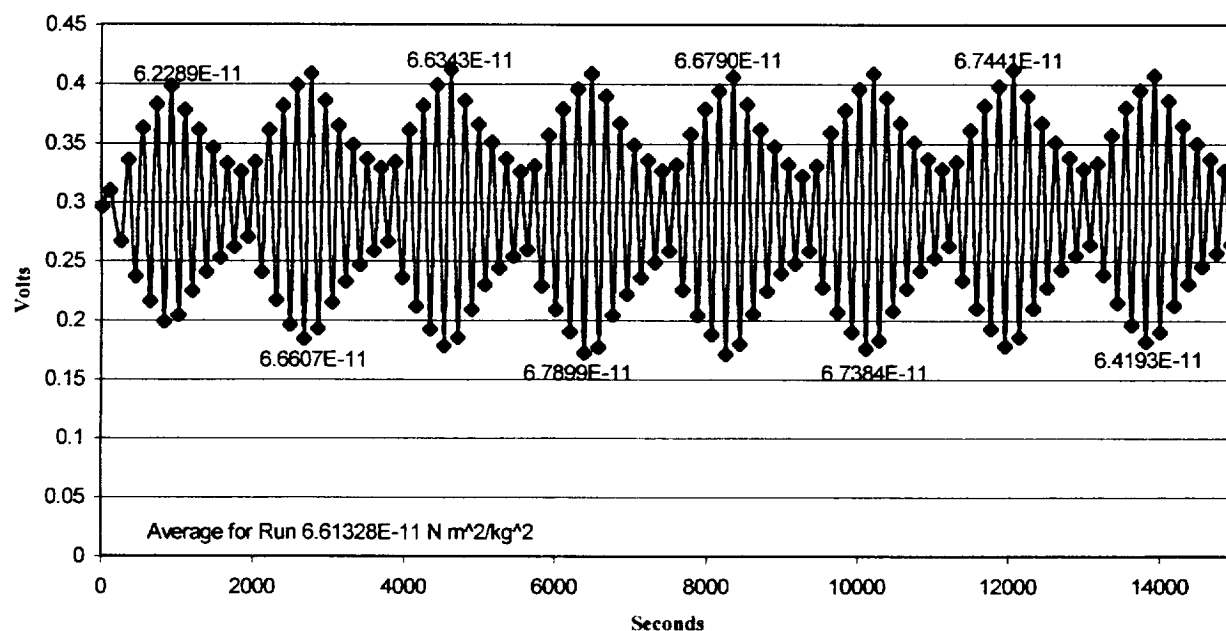
Assembly and Testing

Testing of the system progressed in phases. First the National Instruments computer, stepper motor controller card, controller, and stepper motor were assembled and tested. Then, while the system components were being fabricated a simple tabletop system with pulleys through which the stepper motor moved the large masses back and forth was setup. The purpose of this was to test the software and hardware concepts during development. The data collected from these tests was then reduced by hand to determine if the system was working correctly. When all components had been fabricated the system was assembled and tested on the bench. When it was shown that the system was operating satisfactorily several overnight data runs were made. The system was then placed in the cryostat but not cooled. Runs were again made and the data reduced. It was found that the rate at which the stepper motor accelerated and de-accelerated had to be adjusted to reduce the amount of jerking that occurred in the system. This was done until the reduced data again gave a satisfactory value for the gravitational constant. The balance was then tested in a cooled cryostat at which time it was found that more insulation was required to reach the desired temperature. When more insulation was used it was found that one of the capacitive plates in the balance was bending due to thermal shrinkage. The plate was bending enough to cause inaccurate readings. To alleviate this problem the plate was removed, shortened

slightly and when replaced attached at only one end. It was also found that one of the tracks on the capacitive plates had cracked due to the thermal shrinkage and this too was repaired.

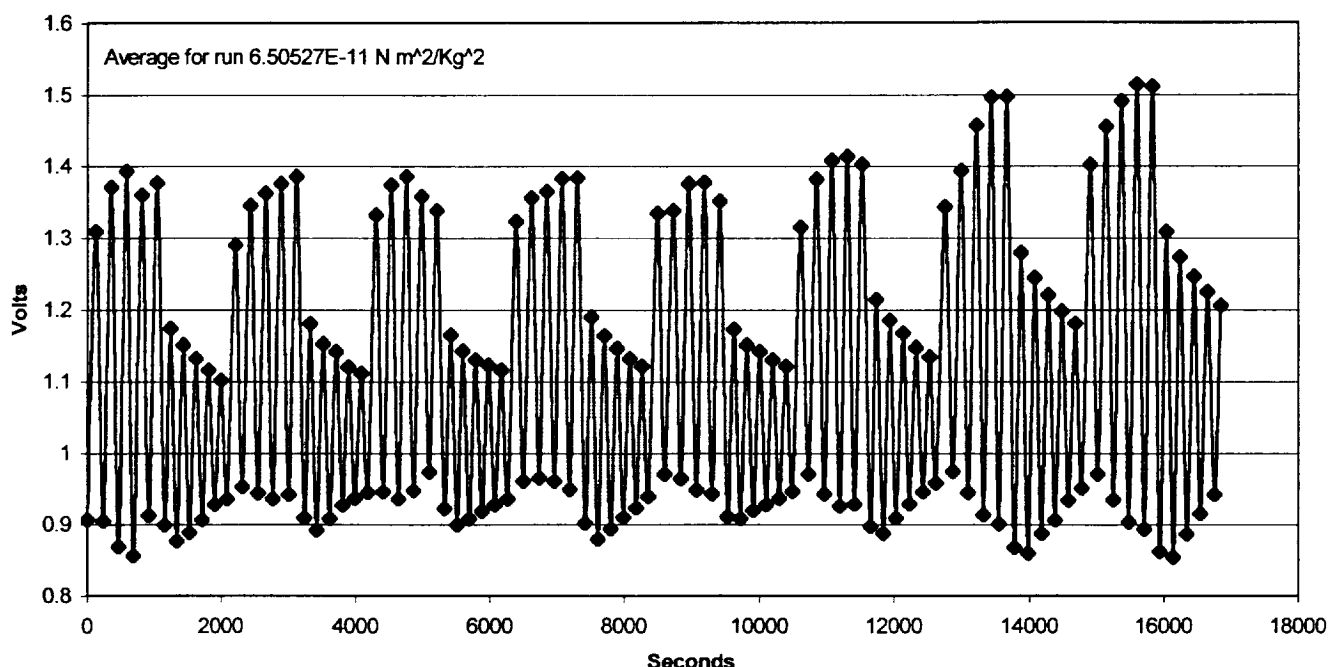
Data

A number of data runs have been made over the last few months. Plot 1 shows about 4 hours of data returned by the peak value detector program from an overnight run. The plot clearly shows energy being input into the system, the system being allowed to damp back down, then the process being repeated over and over. By repeating the process over and over an average value for g can be gotten. The value for g given by TEL-Atomic depends upon the method chosen to reduce the data; for the corrected static method they give a value of $6.276\text{E-}11 \text{ N m}^2/\text{kg}^2$ and a value of $6.869\text{E-}11 \text{ N m}^2/\text{kg}^2$ for the dynamic method. The value we found during testing using the dynamic reduction method was around $6.6\text{E-}11 \text{ N m}^2/\text{kg}^2$, about the average of the dynamic and static values given.



Plot 1. Typical Data

The above plot is for data taken in an un-cooled cryostat, the device has also been tested in a cryostat cooled with liquid nitrogen. The system was cooled by pouring liquid nitrogen into the walls of the cryostat and into the cavity of the cryostat directly under the balance. A type K thermocouple was used to monitor the temperatures in the cryostat. Running tests at the very cold temperatures is more difficult and perturbations to the system that can occur when refilling the cavity of the balance have to be removed before reducing the data. Plot 2 is a plot of data from the balance operated in the cooled cryostat.



Plot 2. Operation in Cold Cryostat

Several things should be noted about Plot 2. The gravitational attraction force value for two cycles was not used in the calculation of the average value for g due to the fact that there were unsymmetrical points in these two cycles leading to unreasonable values. (Not all of the points in each cycle are used in the calculations so some points can appear to be unsymmetrical and a reasonable value for g still be obtained.) Secondly it should be noted that the frequency of the pendulum is different in the cooled cryostat, this is due to two factors, the primary influence

being the fact that the pendulum arm, a tungsten wire, was replaced with a slightly longer wire leading to a longer frequency. Also the wire stiffness was increased due to the cold temperatures offsetting the longer frequency some amount.

Conclusion

During this project an off-the-shelf Cavendish Balance, TEL-Atomic model TEL-RP2010, was modified such that automated operation in a cryostat was possible. A fixture was designed to hold the balance in the cryostat, the drive train was designed to move the masses, and the hardware built and assembled. The control system software was written to collect data and to control the stepper motor driver based upon the data collected. Further software was written to reduce the data collected to a value for the gravitational force between the small and large masses. The system was then tested on the bench top, in the cryostat, and in the cryostat after it had been cooled down with liquid nitrogen.

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